CREA - A Climbing Robot with Eleven Vacuum Adhesion Chambers

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Wall-climbing robots are of great benefit in fields of application, which are dangerous or difficult to handle for humans. But nevertheless, most of the existing systems did not exceed experimental stadium. This paper will present the new climbing robot CREA which makes a step further from a research prototype to a device which can be applied for inspection and maintenance tasks of large concrete buildings. The system uses three driven and steerable wheels for locomotion and eleven individual adhesion chambers. The paper will introduce the hardware and software components as well as aspects for controlling and sensing and show first experimental results with this robot.

Keywords: Wall-climbing robot; vacuum adhesion; concrete surfaces

1. Introduction

Wall-climbing robots are in the focus of research over many years. Most of them did not exceed experimental stadium, while some brought it to application e.g. in the fields of ship building\(^1\) or building cleaning.\(^2\) One challenging field that has not been solved so far are inspection and maintenance tasks of large concrete buildings like river dams, cooling towers, bridge pylons and much more.

Recently, a couple of robotic prototypes have been developed that try to fit this application to enhance building safety and reduce inspection costs. Vacuum adhesion is a very common technique in this field. ALICIA\(^3\) for instance has been developed to move on vertical concrete walls.\(^3\) It consists
of three single units, each equipped with one adhesion chambers and a differential drive, which are connected via an actuated bar. This allows it to lift one segment and to overcome steps which cannot be handled by the drive system. Another system is CROMSCI which also combines a drive system with vacuum adhesion. In contrast to ALICIA3 this robot has only one chassis, but seven adhesion chambers in the shape of spokes allowing it to balance out adhesion forces.

These and other robots have in common, that they did not make it to real application under field conditions. Main problems are the robustness of the hardware components – since the adhesion and motion come with a large stress on the system – and with difficulties in closed-loop controlling and foresighted motion strategies. Other new adhesion technologies like a vortex or electro-adhesion are still under development. Also climbing with spines might be possible but not applicable in the present case. A more decent overview on climbing robots related to inspection and maintenance can be found in.

This paper will introduce the climbing robot CREA which makes a step further from a research prototype to a handy inspection device. Next section 2 will discuss design decisions and their realization and introduce the robot CREA and its subsystems for adhesion and locomotion. Section 3 presents electronic components, sensors and controllers. Afterwards, experimental results will be shown in section 4 and concluded in section 5.

2. Climbing Robot CREA

CREA is a new wall-climbing robot which has been developed in the range of an interdisciplinary research project with partners from research institutes and industry. The goal of this project was the realization of a robust wall-climbing robot which should be able to perform inspection tasks on concrete buildings more efficient and safer than existing approaches.

Figure 1 (left) shows a picture of one of the first test runs of CREA at a concrete wall. The robot chassis is made of carbon fiber for high stability and a low weight and has a dimension of about 1.14 m × 1.03 m. The total weight including all components is about 32.5 kg. Due to high power consumption of suction units and electronics, the robot CREA is externally supplied with power.

The name stands for Climbing Robot with Eleven Adhesion chambers
2.1. Adhesion System

Basis of the adhesion system of CREA is the carbon fiber chassis consisting of two main layers developed by Syntechnics GmbH. The bottom layer contains the eleven adhesion chambers. On the upper plate the two vacuum engines with power electronics are mounted. Both generators are radial blowers of type DOMEL 497.3.230. Each has a power consumption of up to 1 100 W and is able to generate a maximum air stream of 66.5 l/s. These motors have also been selected due to a good ratio of power to weight – which is about 1.2 kg per unit.

The upper plate can be lifted to access the inner part of the robot (figure 1, right). Both layers have been sealed to serve as a vacuum reservoir which is evacuated by the suction engines and distributes it to the eleven individual adhesion chambers which are responsible for robot adhesion. This setup allows a fast regulation of the chamber pressures since the mechanical blowers are comparably slow due to their inertia. Figure 2 (left) shows the bottom of the robot with its eleven adhesion chambers and three circular mounting points for the wheel units.

2.2. Sliding Suction Chambers

The sliding suction chambers are responsible for the adhesion. The contribution of a chamber $i$ to the overall downforce $F$ depends on the pressure difference between chamber ($p_i$) and ambient air ($p_o$) and on the suction area $A_i$ (equation 1). In the present case all chambers are of circular shape with a diameter of 0.18 m. This leads to an effective suction area of 0.025 m$^2$. In total, a chamber consists of elements like seals, sensors and valves.
Fig. 2. A CAD-drawing of Crea’s suction chambers on the bottom (left) and a detailed picture of two different sealing mounting rings made of aluminium and plastic (right).

\[ F = \sum_{i=1}^{11} F_i = \sum_{i=1}^{11} (p_o - p_i) \cdot A_i \] (1)

Inflatable sealings are made of rubber with a sliding surface and create the leak-tightness of a suction chamber. This circular sealing is fixed by two rings which clamp the rubber so that it can be inflated (figure 2, right). The material has been optimized by Guiliard & Doerr GmbH regarding low friction and wear, high adaptability and leak-tightness.\(^9\) The circular footprint allows easy manufacturing and maintenance. So far, the inflatable sealings are supported with pressurized air from an external pressure pump.

Solenoid switching valves of type SMC s070B-5CC adjust the sealing pressure – one for inflating and one for deflating. Therefore, each of the two quick-acting valves is connected to the atmosphere or pressure supply on the one side and to a sealing on the other. These valves have been chosen because of their low weight of only 6.6 g per unit.

Chamber volumes inside of the robot chassis act as control path for closed-loop pressure control. This is important since a certain volume (in this case about 1.9 l) is needed for creating the adhesion pressure.

Chamber valves connect the chamber volumes to the vacuum reservoir to adjust the negative pressure and to counteract losses of vacuum over the sealing edges. Crea uses throttle valves with an inner diameter of 24.5 mm which have been designed to be fast and precise. As actuator, each valve is equipped with a digital servo motor DES 428 BB MG by Graupner. This motor achieves setting and holding torques of 24 N/cm and 50 N/cm respectively at a voltage of 6 V. The weight of one servo motor is only 9.5 g, each assembled valve weights about 68 g. Due to the non-linear relationship between angle and valve opening area, equation 2 determines the area \( A_V \) depending on the radius \( r = 12.25 \text{ mm} \) and the rotation angle \( \alpha \).
A_V(\alpha) = \pi \cdot r^2 \cdot \sin(\alpha) \quad (2)

Pressure sensors are used for each chamber to measure the pressure inside of the sealing and the vacuum inside of the chamber itself. The chamber pressure is monitored by a MXP5100 sensor, for the sealing a MXP5500 sensor is used. These sensors are well suited for the given purpose since they are well calibrated and show a linear output behavior over the full pressure range with a sensor specific offset.

2.3. Locomotion System

The locomotion system consists of three single wheel units, each driven, steerable (two degrees of freedom) and without suspension made by MACCON GmbH. These units are positioned inside of the circular mountings in figure 1 (right) and allow a continuous motion at a velocity of up to 10 m/min in arbitrary directions.

For construction simplicity and an easier maintenance the wheels are located outside of the vacuum system. Integrated load cells HBM U93 deliver data about the current downforces at each contact point between wheel and wall, sliding contacts SM 070 produced by LTN allow an unlimited rotation of the steering axis. The propulsion is generated by a custom MACCON BLDC motor followed by a Harmonic Drive gearbox. The steering angle is adjusted by a standard Faulhaber DC motor with two staged gearing. This configuration forms an omni-directional drive system for high maneuverability and fast and continuous motions.

Fig. 3. Construction drawing of 2 dof drive unit developed by MACCON (left) and picture of upper part (right).
3. Closed-Loop Control Elements

The low level closed-loop control of the adhesion system and the drive units has been realized on a set of digital signal processors (DSP). Each DSP is connected to the control PC via CAN-Bus and to different peripherals like drive engines, chamber valve motors, sealing valves or pressure sensors. In total, four DSPs are used.

One of them – in the present case a Freescale 56F8357 – takes over the low level control functionality of the adhesion system. Different peripherals like pressure sensors and chamber and sealing valves are connected to this DSP via additional electronic connector boards. Most IO tasks are handled by a CPLD chip which is mapped in the memory space of the DSP. The CPLD reads out the analog sensor’s ADC, communicates with the external hardware and loops the switching valve set-points through. DSP and control computer are connected via CAN-Bus.

Figure 4 shows the elements of the used PI-controller for chamber pressure control which follows classic control theory. This controller is able to reduce the current chamber pressure $p_C^{\text{act}}$ by opening the throttle valve to the vacuum reservoir via valve area $A_V$ (compare equation 2). As mentioned before, a raise of the chamber pressure can only be achieved if the airflow over the sealing leakages is larger than the one via the valve opening. Therefore, these leakage areas disturb the control process and have to be balanced out via the valve area.

![Basic closed-loop chamber pressure controller.](image)

Three more DSPs are mounted on the wheel units and responsible for locomotion. Here, processors from Copley are used which communicate with the PC via CAN-Bus and the CANopen protocol. Each controller is responsible for one wheel unit including closed-loop velocity control of the driving wheel, position control for the steering motor and readings from motor encoders, absolute encoders and torque sensors (load cells).
4. Experimental Results

With CREA every suction unit has its own sealing that can be controlled separately. Compared to Cromsci this provides an additional degree of freedom (DOF) for the control of the single suction unit.

In a first experiment the normal force produced by the seals is investigated. Figure 5 shows the change in normal force recorded by the load cells at each wheel while two of the seals are inflated sequentially. As it can be seen the normal force decreases with the rising pressure in the sealing as it compensates the pressure. The variation in the normal force compensated by the two seals is caused by the different sealing materials resulting in different deformation. During locomotion this normal force induced by the seals has two negative effects. Firstly it increases the friction caused by the seals resisting locomotion and thus resulting in wear of the seals. Secondly it reduces the normal force acting on the wheels and thereby reduces the grip needed for propulsion.

![Fig. 5. Absorption of sealing normal force $F_N$ in [N] by sealing pressures $p_{S2}$ and $p_{S3}$ in [10 mBar].](image)

The goal of current research is the development of a control system that is able to minimize the normal force of the sealing system during locomotion. In the optimal case it is possible to have no contact at all by adjusting a very small gap between the sealing and the opposing surface. This would increase the usability of the system on large concrete structures significantly by reducing the wear of the seals and the wheels.

Based on simulation results and first experimental test runs it is expected that CREA is able to create adhesion forces between 2 000 and 3 000 N. But this strongly depends on the ground structure, the basic chamber leakages and the number of active suction units.
5. Conclusion

This paper introduced the new wall-climbing robot CREA which adheres to concrete walls via negative pressure and uses wheels for locomotion. The robot will make a step towards an applicable inspection device for large concrete structures. Recent experiments have shown the general operability of the system although CREA is still in the integration phase.

Therefore, future work will focus on the optimization of the components and closed-loop controllers to perform tests showing the robustness of its hard- and software. Also the embedding of inspection devices including sensors and a manipulator are in progress and will be done in the future.

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References